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Cavitation Along Surfaces of Separation

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By means of a moving picture accompanying this presentation, the author demonstrates the development of cavitation in flow along a two-dimensional surface of separation. This film has been chosen as the best means of presenting some of the qualitative characteristics of this type of cavitation which are important to engineers concerned with cavitation in diverse practical situations. A description of the experiments, some views from the movie, and a discussion of the observations of cavitation in a zone of separation are given in the paper.

The majority of engineers concerned with various aspects of cavitation are especially interested in well-streamlined flows such as in the passages of pumps and turbines, through tunnels, over spillways and around the propellers of ships and submerged bodies. Therefore, it is natural and best that primary attention has been given to cavitation associated with these various boundary forms. In many studies the presence of separation and the possibility of cavitation originating along surfaces of separation has been recognized. However, most of the studies reported in the engineering journals have not been concerned primarily with this ocurrence. On the other hand, there has been much interest in the basic structure of flow in a zone of separation in the absence of cavitation, with much of the work in this area being of a theoretical nature. The exploratory study described here was undertaken in an attempt to bridge the gap between these two areas of endeavor. Initially qualitative information both on cavitation and on the development of vortices and/or turbulence along surfaces of separation was sought by direct photographic observation. Even the initial results were found to be very revealing. To make them immediately available to other investigators as well as to engineers in practice, the films have been prepared for presentation.

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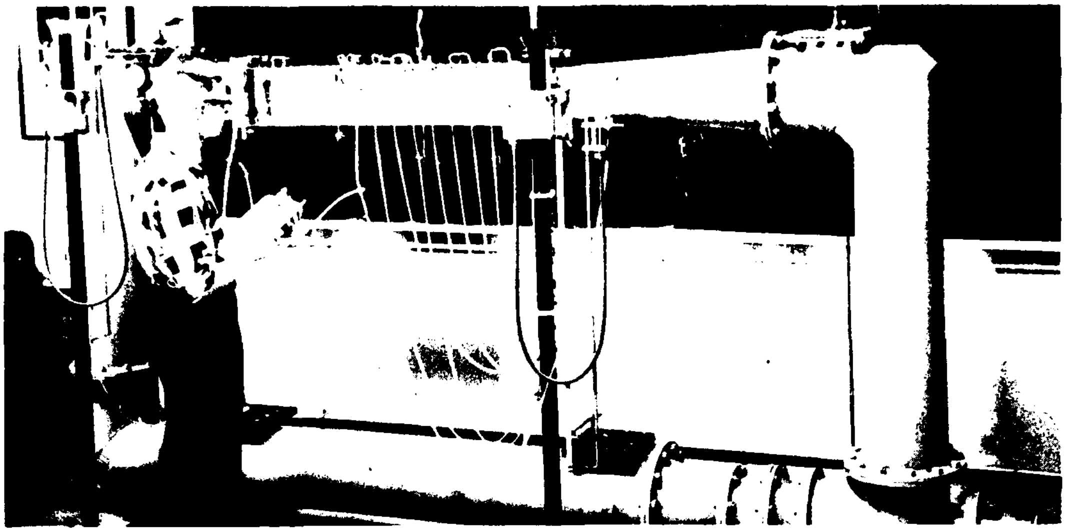

Fig. 1 Water tunnel used in experiment

EXPLORATORY EXPERIMENT

An existing small recirculating water tunnel in the Fluid Mechanics Laboratory of the University of Kansas was adapted for a first close look at flow along a surface of separation. The main ducts of the tunnel, Fig.1, are 10 in. diam with vaned elbows. Flow produced by a Peerless axial-flow hydrofoil pump passes through a honeycomb to insure against rotation of fluid in the tunnel and thence through a well-streamlined contraction into a rectangular test section 3 in. wide by 6 in. high and 48 in. long made of clear acrylic plastic. Further contraction was provided by an insert in the test section forming a nozzle 3 in. square followed by an abrupt expansion to 6 in., as shown in Fig.2. Thus, a surface of separation was formed along a horizontal central plane in the test section. With a width of section of only 3 in., absolutely two-dimensional flow was not assured, but the effects of side-wall boundary layers were easily distinguishable. In these initial qualitative observations, no adverse effects were encountered because of the side walls.

Movies of the flow along the surface of separation were taken with a 16-mm Cine-Kodak Special camera provided with a contactor to trigger a microflash lamp each time the shutter opened. The camera was mounted at the same level as the center line of the test section and in front so that flow is from left to right in the photographs which follow. The flash lamp was placed directly below the test section so that reflections were observed from cavities and gas nuclei in the flow. A film speed of 64 frames per sec was used for the initial pictures.

In Figs.3 and 4 enlargements of individual frames of the film are reproduced, the first showing the first 9 in. of the flow starting at the abrupt expansion (visible in the upper left-hand corner of the picture) and the second extending from 3 to 12 in. from the expansion. These reveal a certain regularity in cavity formation which must be associated with reduced pressure within individual vortices. Growth of the vortices is evident. The small filament of bubbles linking adjacent main cavities occurs due to the boundary layers on the side walls. The process can be described in this way. Initially, an essentially two-dimensional vortex is generated near the beginning of the surface of separation. The ends of the vortex lie in the boundary layers on the side walls and consequently do not have as large a translational velocity as the main part of the vortex. As the ends of the vortex begin to trail behind, their motion becomes influenced by flow in the boundary layers, which itself follows the counter-clockwise rotation of fluid in each main vortex. The trailing vortices thus are deflected downward by circulation in one main vortex and upward by the following vortex. In this process, the ends of the vortices are stretched which results in their becoming smaller in diameter and faster in rotational speed. As a result, cavitation initially occurs within these trailing vortices, as shown in Fig.5.

COMPARISON WITH JET CAVITATION

Studies of cavitation in the mixing zone of submerged circular jets at the Iowa Institute

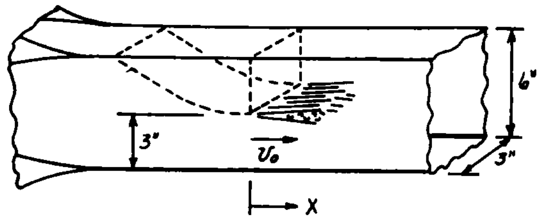

Fig. 2 Dimensions of abrupt expansion

(1,2)[1] revealed very little if any regularity in the formation of vortices along the surface of separation. From the beginning, the fluctuations in flow appeared to take on a randomness characteristic of turbulence. In contrast, vortices developed with regularity in the bounded expansion. This raises the question as to whether the eddy between the zone of separation and the walls of the expansion in some way controls the formation of vortices in a periodic fashion. The only other evidence found to indicate that this might be the case is a photograph of cavitation around a circular disk taken at Caltech (3). In Fig.10 of this reference, two successive areas of cavitation are revealed, though only one is labeled. Although no definite conclusion can be drawn from this limited evidence, it is apparent that regular vortices are created along surfaces of separation under some conditions and perhaps these are associated with flows having distinct and limited areas of separation. Additional information on this subject is needed to better understand the development of flow in the diverse situations where separation occurs.

PRACTICAL IMPORTANCE OF SEPARATION-CAVITATION

In general the value of the cavitation parameter

$$K_1 = (p_o - p_v)/(\rho V_o^2/2)$$

for incipient cavitation is higher where separation exists than it is for streamlined flows. Thus, there is always a possibility that where cavitation is unexpectedly encountered, separation also exists even though it may not have been expected. One example of this was recently encountered where noisy operation of a pump arose due to cavitation. In this case, maximum noise occurred at shutoff when the static pressure in the pump was a maximum and net flow was zero. In this case separation, apparently in the scroll case, was the cause of cavitation.

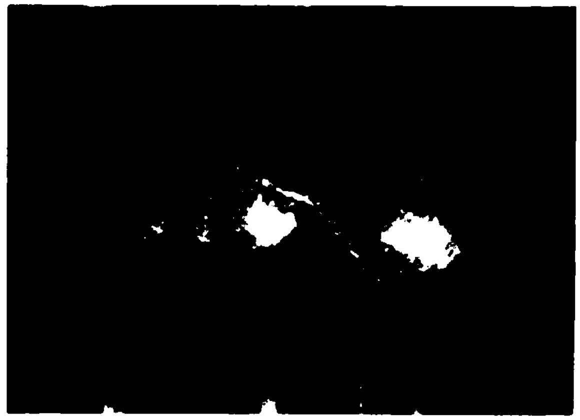

Fig. 3 Cavitation at abrupt expansion. X = 0 to X = 9 in.; K = 0.4; Uo = 34 FPS

When separation occurs, it is no longer necessary that the mean pressure in the flow approach the vapor pressure of the fluid. Within transient vortices, the local pressure may be lower than the mean pressure by 50 per cent or more of the dynamic pressure of the flow, $\rho V_o^2/2$. The extent to which vortices locally reduce pressure in the flow, the relationship between vorticity and minimum pressure, and the spatial development of vortices along surfaces of separation are all important characteristics of this phenomenon which need to be investigated. Once this information has been obtained, scaling relationships for this type of cavitation can be established.

DEVELOPMENT OF SCALING PARAMETERS

The factors affecting onset of cavitation along surfaces of separation are essentially the same as those for boundary layers as described by Daily and Johnson (4). Their studies indicate that the incipient cavitation index may be expressed by a relationship of the form

$$K_1 = C_p + K_t = \frac{p^*}{\rho V_o^2/2}$$

To make the relationship applicable to flow along a surface of separation, slightly different definitions of the first two terms on the right are introduced here, as follows:

$$C_p = \frac{p_o - p}{\rho V_o^2/2}\text{, pressure coefficient}$$

p_o = reference pressure

p = average pressure at point of inception of cavitation

[1] Numbers in parentheses designate References at the end of the paper.

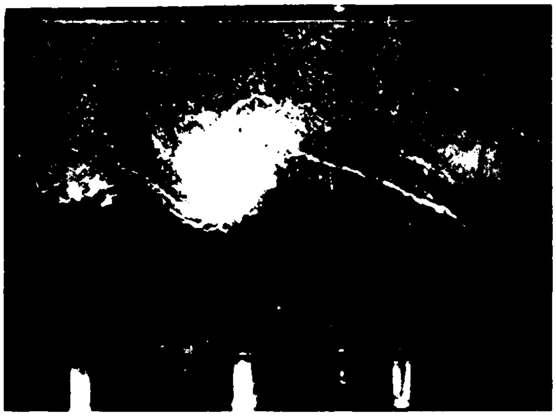

Fig. 4 Cavitation at abrupt expansion. X = 3 in. to X = 12 in.; K = 0.4; Uo = 34 FPS

Fig. 5 Incipient cavitation at abrupt expansion showing cavities in trailing vortices

$K_t = \dfrac{p - p_{min}}{\rho V_o^2/2}$, a pressure-difference parameter representing reduction of pressure in vortices along surface of separation

$\dfrac{p^*}{\rho V_o^2/2}$ = critical-pressure parameter indicating pressure at which gas nuclei will become unstable and tend to increase in size without limit

Daily and Johnson have shown that in flows at high velocity (30 fps or more) with macroscopic nuclei present (.001 in. or more), the effect of the last parameter is negligible. Furthermore, data on the pressure coefficient Cp are already available for abrupt expansions (5), so that observations of the inception of cavitation from nuclei will permit calculation of K_t. The magnitude of this factor will certainly depend upon the Reynolds number of the flow and to some extent on the geometry of the approach to the abrupt expansion. However, there is a prospect of correlating K_t with Reynolds number and thereby completing the last step needed to formulate a scaling law for separation-cavitation. Certainly the law would have to be confirmed for flows in which the parameter representing the effect of surface tension,

$$\frac{p^*}{(\rho V_o^2/2)}$$

is not negligible. However, this approach, developed by Daily and Johnson, holds real promise for it separates the effects dependent upon viscous and surface forces.

Acknowledgment

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